CURRENT SENSE SHUNT RESISTOR CIRCUIT

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001]   The present invention relates generally to sensing output current in an electrical circuit. The present invention relates more particularly to a shunt resistor connected to an electrical circuit output to measure the current of the output.

2. Description of Related Art

[0002]   A number of electrical applications, in particular power applications, take advantage of output current sensing to provide feedback control for the electrical circuit or system. Typically, the output current is sensed by measuring a voltage drop across a highly precise resistance to thereby determine the current flowing through the resistance related to the measured voltage drop. Because this technique inherently requires a voltage drop, there is often a large amount of power dissipated in the resistance with large current flows. Indeed, because power equals the resistance times the current squared, increasing current determines an increase in power dissipation proportional to the square of the current.

[0003]   To solve this difficulty, the precise resistance is employed as a shunt resistance that is as low as possible to reduce power dissipation. However, when the shunt resistance is reduced, the measurable voltage drop across the shunt resistance decreases as well. As a result, the dynamic range of the measurable voltage drop decreases significantly. With the limited dynamic range resulting from the lowered shunt resistance, the accuracy and precision of voltage measurements is degraded.

[0004]   As an example, a typical shunt resistance is composed of manganin, which is suitable for use in high current applications where current sensing is desired. Typical characteristics of commonly used manganin shunts are provided in Table 1 below.

Table 1: Manganin shunt characteristics

Parameter	Value	Unit	Symbol
Thermal Coefficient	~50	ppm/°C	α_m
Resistance	0.3 and up	mΩ	R
Precision	1	%	-
Thermal resistance	15	°C/W	R_{th}
Maximum power dissipation	5	W	P_{max}

[0005]   A review of the data in Table 1 reveals several useful conclusions regarding the use of low resistance manganin shunts. For example, the thermal resistance of the shunt is fairly high causing an increase in shunt temperatures due to heat and resistance power dissipation. For example, with a 2mΩ shunt in an application calling for the measurement of a 50A output, the change in temperature due to the thermal resistance is given by the following equation.

[0006] $\Delta T = 2m\Omega \cdot (50A)^2 \cdot 15°C/W = +75°C$

[0007]   The maximum allowable power dissipation permitted by the manganin shunt limits the maximum dynamic voltage range as current through the shunt increases. Accordingly, in the higher range of measured current there is a loss of precision in reading the voltage drop across the shunt.

[0008]   Given a typical power dissipation through the manganin shunt of 5W, the shunt resistance varies among different measured current output applications. A summary of output current, shunt resistance and dynamic voltage range for the shunt is provided in Table 2 below.

Table 2: Voltage dynamic across a resistive shunt

Max Current	Shunt R	Dynamic	Power
±50 A	2 mOhm	±100 mV	5W
±100 A	0.5 mOhm	±50 mV	5W
±150 A	0.22 mOhm	± 33 mV	5W
±200 A	0.13 mOhm	±25 mV	5W

[0009]   The data from Table 2 indicates that as the application current increases, the dynamic range available through the appropriately sized shunt resistor decreases. The measurable quantities of changing voltage related to current are thus reduced in higher current applications, making accurate current measurement problematic.

[0010]Accordingly, there is a need for a current sensing circuit for use with high current applications with a dynamic range more useful for precision measurements.

SUMMARY OF THE INVENTION

[0011]   According to the present invention, a shunt circuit for sensing current in an electrical circuit output with an increased dynamic range is provided. The shunt circuit provides a resistor in parallel with the shunt resistance to obtain a current divider. The parallel resistor acts as a current sense resistor with a gain in relation to the shunt resistor that can be chosen to obtain a preferred value for a current sensing dynamic range.

[0012]   A compensation circuit is connected to the current sense resistor to compensate for temperature variations over a broad range of current output values. According to one embodiment, the compensation circuit is adjusted in a setup phase for the specifics of the application, and then placed in sensing mode to obtain current sense measurements. According to another embodiment, a dynamic range for a given precision is calculated and applied by adjusting circuit parameters in a setup phase. According to another embodiment of the present invention, a configuration for calculating permanent settings of circuit components to obtain a desired gain and precision is provided.

[0013]   The current sensing shunt resistor circuit according to the present invention is configured to be substantially independent of thermal variations and changes in dynamic thermal ranges. The current sense shunt resistor circuit can be implemented on an integrated circuit with standard IC processes to further improve power dissipation characteristics. In addition, circuit component values can be set permanently, or changed dynamically through electronic programming.

[0014]   Other features and advantages of the present invention will become apparent from the following description of the invention which refers to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015]   Fig. 1 is a schematic overview of the current sense shunt resistor circuit according to the present invention;

[0016]   Fig. 2 is a circuit diagram illustrating functionality of the current sense shunt resistor circuit according to the present invention;

[0017]   Fig. 3 is a graph of current temperature coefficient versus temperature for the current sense shunt resistor circuit according to the present invention;

[0018]   Fig. 4 is a circuit diagram of an embodiment according to the present invention;

[0019]   Fig. 5 is a circuit diagram illustrating the current sensing shunt resistor circuit according to the present invention implemented as an IC with external connections; and

[0020]   Fig. 6 is an illustration of a resistor network that can be configured to provide a desired gain precision for the current sensing shunt resistor circuit according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0021]   Referring now to Fig. 1, the current sense and shunt resistor circuit is shown generally as sensing circuit 10. Circuit 10 includes a current shunt 12 that measures current in an output circuit by driving a voltage across shunt 12. Circuit 10 is in the form of a current divider that provides two parallel paths for shunt current, including a path through a sensing resistor 14. Circuit 10 includes a voltage buffer 16 to control current between the two parallel shunt paths. By making sense resistor 14 have the same voltage as shunt resistor 12, sense resistor current i_{se} is determined according to the following equation.

[0022]
$$i_{se} - I_{SH} \cdot \frac{R_{SH0}}{R_{se0}} = \frac{I_{SH}}{G} \qquad (1)$$

[0023]   In equation 1, i_{se} is the sense resistor current, I_{SH} is the shunt resistor current, R_{SH} is the shunt resistor resistance value, R_{se} is the sense resistor resistance value and G is the gain ratio determined by the values of the shunt and sense resistors. Circuit 10 can be arranged and operated so that a value for G can be chosen to obtain a fixed value for a dynamic range of operation for current i_{se}.

Current i_{se} can be measured as an output of circuit 10 to obtain a wide range of current sensing with sufficient precision to permit the use of circuit 10 in a wide variety of applications.

[0024]   Referring now to Fig. 2, voltage buffer 16 is shown as a biasing voltage 20 and an operational amplifier 22 coupled to a MOS-gated transistor 24. The components making up voltage buffer 16 permit current i_{se} to be positive in sign across sense resistor 14. Since current I_{SH} in shunt resistor 12 can change sign, biasing voltage 20 maintains current i_{se} in the positive direction to bound the sense current in a positive range as referenced. With this biasing voltage, the equation describing current i_{se} changes.

[0025]
$$i_{se} = \frac{V_B}{R_{se}} + I_{SH} \bullet \frac{R_{SH}}{R_{se}} \qquad (2)$$

[0026]   From equation 2, it can be observed that i_{se} is related to the biasing voltage V_B (20), the sensing resistor R_{se} (14) and the ratio of the shunt resistor R_{SH} (12) and the sensing resistor R_{se} (14). The ratio of shunt resistor 12 to sensing resistor 14 dictates the gain between the shunt current I_{SH} and the sense current i_{se}. That is, $R_{SH}/R_{se} = 1/G$. In equation 2, sensing resistor 14 has a thermal coefficient that is set as close as possible to shunt resistor 12 to obtain appropriate compensation. In addition, if the term of equation 2 that includes biasing voltage V_B can be compensated, or removed, then equation 2 becomes equation 1.

[0027]   It is well known that resistor power dissipation is limited for practical resistors, and that temperature of resistors increases with increased current flow due to high thermal resistance as well as pure electrical resistance and the associate heat that is generated. Accordingly, as the temperature of circuit 10 increases, the changing range of measurement for the shunt and sense resistors must be

compensated to obtain an unchanging and useful dynamic range of current sensing. The relationship between the sense current i_{se} and temperature is illustrated below, in which equation 1 is rewritten to incorporate thermal resistance factors in terms of resistor characteristics and changes in temperature.

[0028]

$$i_{se} = I_{sen} \frac{R_{SH0}(1+\alpha_1 \cdot \Delta T)}{R_{se0}(1+\alpha_2 \cdot \Delta T)} = \frac{I_{sen}}{G}(1+ITC \cdot \Delta T)$$

(3)

[0029] In equation 3, R_{SH0} and R_{se0} represent the values of R_{SH} and R_{se} at 25° C. The thermal coefficients of the resistors are represented as α_1 and α_2, of the sense and shunt resistors, respectively. The term ITC represents the current temperature coefficient for the combination of shunt and sense resistors in equation 3, with the approximation being made according to the conventions of equations 1 and 2.

[0030] If the approximation in equation 3 is made to be equal, the ITC term can be resolved in terms of the temperature coefficients of the shunt and sense resistor.

[0031]

$$\frac{\left(1 + \alpha_2 \bullet \Delta T\right)}{\left(1 + \alpha_1 \bullet \Delta T\right)} \equiv 1 + ITC \bullet \Delta T \Rightarrow ITC = \frac{\alpha_2 \bullet (\rho - 1)}{1 + \frac{\alpha_2}{\rho} \bullet \Delta T}$$

(4)

[0032] The representation of ITC includes the ratio of the thermal coefficients, $\rho = \alpha_1 / \alpha_2$, which represents the mismatch between the shunt and sense resistors. The thermal coefficients can be determined for the resistors, although only approximately. For example, α_2 is approximately equal to 4200ppm when shunt resistor R_{SH} (12) is made of aluminum.

[0033]   An analysis of equation 4 shows that the current temperature coefficient

ITC is non-linear over temperature. Referring to Fig. 3, a graph is provided

illustrating ITC for two different metal resistors prepared in an integrated circuit

process. One integrated circuit process for forming a resistor using a two metal

composition with thicknesses of 20 micrometers and 0.6 micrometers, and with

thicknesses of 20 micrometers and 1.2 micrometers, produced resistors with thermal

coefficient ratio values of $\rho = 1.086$ and $\rho = 1.04$. Fig. 3 illustrates the plots of these

two resistors thus obtained, with a gain value of $G = 100,000$, so that the ratio of

$i_{se}/I_{SH} = 10\mu A/A$.

[0034]   In viewing the results illustrated in Fig. 3, it becomes clear that (1) ITC

decreases with temperature, and (2) ITC is non-linear over temperature, i.e., ITC is a

function of temperature. As the ratio of thermal coefficients ρ approaches 1, the

sensed current values become less temperature dependent and more linear. This is

the case, even if a strongly temperature dependent material is used to form the shunt

and sense resistors 12, 14. Accordingly, by providing the sense resistor in

combination with the shunt resistor, and adjusting the ratio of the thermal

coefficients between the two resistors, compensation can be provided to obtain a

linear current sense with a wide dynamic range, an important feature of the present

invention.

[0035]   Biasing voltage V_B (20) is introduced to maintain the sense current i_{se} in a

positive direction. Equation 2 illustrates the introduction of the biasing voltage with

the biasing term V_B/R_{se}. This biasing term introduces an error that changes as a

function of temperature. A robust design for obtaining linear results for a sense

current over temperature depends upon compensating this biasing term.

[0036]   The reason the biasing V_B/R_{se} is dependent on temperature is because of

the temperature coefficient α_1, which includes consideration of changes in resistance

over temperature. The resistance value of R_{se} is proportional to temperature, which

indicates that the ratio ov V_B/R_{se} is hyperbolic with regard to temperature. The term V_B/R_{se} can be cancelled from equation 2 using a number of techniques, one exemplary technique being presented below. It should be recognized that the present invention contemplates a number of possible solutions to cancel this term from equation 2, based on the knowledge of the term as described above.

[0037]   Referring now to Fig. 4, a diagram of a circuit useful for applying a method to cancel the V_B/R_{se} term from equation 2 is shown generally as circuit 40. Circuit 40 more closely models the actual operating parameters of the shunt current sense circuit, with the inclusion of parasitic resistances R_p (42) and R'_p (44). In addition, two switches, ph (46) and phN (48) are provided to connect or disconnect the various circuit sections. Circuit 40 is first analyzed by solving for sense current i_{se} in the loop indicated by arrow 45, with switch 46 closed and switch 48 open. In this condition, sense current i_{se} can be written according to the following equation.

[0038]
$$i_{se} = \frac{V_B}{R_{se}} + \frac{i_B \bullet R'_p}{R_{se}} = \frac{V_B}{R_{se}} + \varepsilon \qquad (5)$$

[0039]   The current i_B in equation 5 represents a current flowing in correspondence with the biasing voltage V_B while switch 46 is on and switch 48 is off. While equation 5 holds for the circuit, a voltage loop indicated by arrow 45 permits an independent value for current i_{se} to be determined and stored as a base value. When switches 46, 48 are reversed, so that switch 46 is off and switch 48 is on, the circuit becomes approximately the same as that indicated in Fig. 2, and equation 2 describes the resulting circuit operation. Accordingly, using the initially determined sense current i_{se} as a base value, equation 5 can be subtracted from equation 2 to obtain a description of the operation of the resulting circuit 40.

[0040]
$$i_{se} = \frac{V_B}{R_{se}} + I_{SH} \bullet \frac{R_{SH}}{R_{se}} - \frac{V_B}{R_{se}} - \varepsilon = I_{SH} \bullet \frac{R_{SH}}{R_{se}} - \varepsilon \qquad (6)$$

[0041] The error term ε is a current value that is extremely small and negligible with regard to most applications. For example, if current i_B equals 25 μA, R'_p equals 10mΩ and R_{se} equals 29Ω, ε is equal to approximately 0.008 μA. That is, over the range of operation, if current I_{SH} equals 1 amp, which would imply that current i_{se} equals 10 μA, then ε as a percentage is equal to 0.008 μA/10 μA sensed, or about 0.08%. In addition, it is possible to read a value for current i_{se} using circuit 40 by measuring the voltage, V_{out} across the supply resistor R_{out}.

[0042] Using the above technique accompanied with the switching action in circuit 40, the term V_B/R_{se} can be cancelled from equation 2, with only a negligible error factor present in the resulting sensed current i_{se}. The switching circuit, biasing voltage and other components used to obtain the result of equation 6 can be realized individually on a separate current sensing IC.

[0043] Referring now to Fig. 5, current sensing IC 50 is illustrated in dashed lines as encompassing switches 46 and 48, biasing voltage V_B, op-amp 22, MOS-gated transistor 24 and supply resistor R_{out} The external connections to current sensing IC 50 are shown for connection to the shunt and sense resistors to obtain the overall current sense circuit 40.

[0044] Precise ratios between R_{se} and R_{SH} are usually required by users (less than or equal to 1%). Linearity of current sensing is not necessarily effected by a mismatch of R_{se} and R_{SH}, if this mismatch is fixed. To obtain these precise relationships, the resistors R_{SH} and R_{se} are trimmed according to a particular trimming method. For example, a current is applied to the shunt resistor R_{SH} and the sense resistor R_{se} with the goal of obtaining a current divider with a gain of G equals 100.000 ± 1%.

[0045]   The highly precise and accurate gain value is obtained by comparing the current through the two different resistors with respect to the desired gain of the resistor ratio value. The following equation provides a percentage error obtained through direct measurements that indicates the appropriate changes made to the resistor trimming mechanism to obtain the desired gain. Because the equation takes into account the nominal current through the shunt resistor, the gain error is sensitive to the range of operation for the particular current sensing application.

[0046]

$$\% \text{ error} = \frac{I_{se\,meas} - I_{nom}/G}{I_{nom}/G}\% \qquad (7)$$

[0047]   Equation 7 uses a nominal current forced through the shunt resistor of I_{nom}, for comparison with the current forced through the sense resistor, $I_{se\,meas}$. The percentage error obtained by equation 7 indicates how the sense resistor can be changed to achieve a highly precise and accurate gain after trimming.

[0048]   One trimming mechanism that can be used according to this method is to supply an array of resistors that comprise sense resistor R_{se}. Such an array is illustrated in Fig. 6 as network 60. A number of fuses, fuse 0-fuse 7, are supplied to permit or prevent conduction down various branches of network 60 to change the resistance of the overall sense resistor R_{se}. In accordance with an embodiment of the method of the present invention, a current is forced through shunt resistor R_{SH} leading to a forced current supplied through pins 62 and 64 in Fig. 6. A look-up table is provided according to the measured sense current $I_{se\,meas}$, so that an error

percentage can be determined according to equation 7 to indicate which of fuses 0-7 should be blown to obtain the appropriate resistance value for sense resistor R_{se}.

[0049] For example, if a nominal current of one amp is applied through shunt resistor R_{SH}, the ratio of $I_{nom}/G = 10 \mu A$. If current $I_{se\ meas}$ is measured at 9.28 μA, the resulting error percentage is -7.20 %. Referring to Table 3 below, a value for the error percentage identifies a corresponding fuse configuration that will achieve the desired accuracy and precision in the gain between the two resistors.

TABLE 3

$\dfrac{I_{se\ meas} - {}^{I_{nom}}\!/G}{I_{nom}/G}\%$	Fuse configuration MSB to LSB	Residual error
...	...	...
-7.50%	11100100	-0.22%
-7.40%	11100100	-0.11%
-7.30%	11100100	0.00%
-7.20%	**00101000**	**0.06%**
-7.10%	11000100	-0.01%
-7.00%	11000100	0.10%

[0050] In the above example, the measured error percentage of -7.20% provides a fuse configuration identified as 00101000, which can also be viewed as a bit configuration, to indicate that fuse 3 and fuse 5 should be blown. Once fuse 3 and fuse 5 have been blown according to any particular method, the resulting sense resistor R_{se} should provide a highly precise and accurate gain as desired for a nominal current of 1 A in shunt resistor R_{SH}. In accordance with the contents of the trimming

look-up Table 3, the residual error for the newly determined gain should be approximately 0.06%, which should supply the resulting gain of $100.000 \pm 1\%$.

[0051]   The look-up table exemplified by Table 3 is derived from solving the circuit equations of the trimming resistor network 60. A number of techniques are available to obtain this look-up table, including computer programs and rote circuit analysis calculations. The resulting trimming look-up table provides combinations of fuse interruptions that produce a resulting voltage output on pin 66 in Fig. 6, for example, for a given current. The program to calculate the various combinations of fuse interruptions and the resulting changes in sensed output uses the resistor values for R_{SH} and R_{se}, as well as the values of the resistors R_1-R_7 illustrated in Fig. 6, for example, and the various paths P_0-P_7 that connect the resistors R_0-R_7 with the trimming fuses fuse 0-fuse 7. The labels for the circuit points in Fig. 6 correspond to those provided in Fig. 4, for example. In addition to calculating the various resulting error percentages based on blown fuse combinations, the program calculates the residual error differences between the target values and the desired value after choosing the fuse configuration that minimizes the residual error difference.

[0052]   According to the method of the exemplary embodiment, a trimming procedure is accomplished as follows. First, a nominal current I_{nom} is forced in shunt resistor R_{SH}. The current in sense resistor R_{se} is measured to obtain the value for $I_{se\ meas}$. The error percentage ratio in equation 7 is calculated using the values for the nominal current and the measured sense current, together with the ratio of the sense and shunt resistor values. The resulting error percentage is used to identify the entry in the lookup table, e.g., Table 3 that corresponds to the appropriate fuse configuration. The appropriate fuses indicated in the values in Table 3 are blown to obtain the desired value for the sense resistor R_{se}, and the error percentage is calculated to obtain the residual error that should be less than or equal to that illustrated in the third column of Table 3.

[0053]   Using the resistor network 60 illustrated in Fig. 6, it is possible to use the above-described procedure to trim resistor values with an initial ± 24% mismatch to within ± 1%.

[0054]   The low ohmic shunt resistor discussed above provides a precise and accurate solution for measuring current in high current applications that typically involve common shunt resistors. A scalable dynamic range sense current is obtained that is independent of the shunt resistor value. The circuit described provides good thermal coefficient properties to obtain a more linear current measurement over a range of temperature and current values. By packaging the sensing and control mechanism in a single IC, for example, typical IC heat and power dissipation mechanisms can be used to further lower thermal resistance and improve current sensing operation. By providing a technique for trimming the sense resistor, which can be accomplished electronically, a gain precision of better than 1% can be obtained. It should be noted that the trimming mechanism for the sense resistor can be accomplished in any number of methods, including through the provision of an automatic trimming circuit that can produce a forced current, measure sensed current, calculate error percentages and automatically blow specific fuses in a resistor network to obtain a highly precise sense resistor value in comparison with overall circuit operation.

[0055]   Although the present invention has been described in relation to particular embodiments thereof, many other variations and modifications and other uses will become apparent to those skilled in the art. It is preferred, therefore, that the present invention be limited not by the specific disclosure herein, but only by the appended claims.